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Embodied Carbon as a Material Selection Criterion: Insights from Sri Lankan Construction Sector

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Abstract: The choice of materials is crucial in responding to the increasing embodied carbon (EC) impacts of buildings. Building professionals involved in material selection for construction projects have a vital role to play in this regard. This paper aimed to explore the extent to which building professionals in Sri Lanka considered EC as a material selection criterion. A questionnaire survey was conducted among a sample of building professionals in Sri Lanka. The results indicated that the consideration of EC as a material selection criterion remained low among key professionals, such as architects, engineers, and sustainability managers, despite their reasonable influencing powers and knowledge of EC. Those respondents who had considered EC as a selection criterion said they had been primarily driven by green building rating systems and previous experience. Those respondents who had not considered EC during material selection commonly reported that they had been prevented from doing so by the lack of regulations and the lack of alternative low carbon materials. Respondents believed that the involvement of actors, such as the government, professional bodies, environmental organizations, activist groups, and the public, may be significant in promoting the greater consideration of EC during material selection.

Keywords: embodied carbon emission; material selection; building professionals; Sri Lanka

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1. Introduction

Together, the building and construction sectors consume large quantities of materials, and one-third of global energy [1]. They are responsible for nearly 39% of global carbon emissions [2]. Nevertheless, they have more significant opportunities for reducing carbon emissions in the short term compared to other major carbon-emitting economic sectors, such as transportation, energy generation, agriculture, forestry and other land use, and product manufacturing [3,4]. In response, building regulations and voluntary measures, such as building rating systems, were introduced. However, owing to the larger share (40%–60%) of whole building life carbon, the main focus until recently was given on reducing operational carbon (OC) emissions associated with energy use in building operational activities, such as heating, cooling, light, and other electronic and electrical appliances [5–7]. As a result, buildings became more energy efficient in terms of OC, but enabled the EC to gain a larger proportion (40%–70%) of whole building life carbon [8]. Notably, the whole life carbon of zero-carbon buildings solely comprised EC [9]. Therefore, EC is now increasingly viewed as an important aspect of whole life building carbon emissions [7,10]. Policymakers together with researchers and building professionals currently focus more on EC while reducing OC to meet zero carbon building targets in future.

EC is defined as the total impact of all the greenhouse gas (GHG) emissions caused by extraction, manufacture/processing, transportation, assembly, maintenance, replacement, deconstruction, disposal, and end-of-life aspects of the materials and systems that make up the building [11]. These emissions arise from the consumption of energy (embodied energy (EE)) and inherent chemical processes of materials (e.g., cement) [12,13]. Over the lifecycle of a building, all the phases contribute to EC emission impacts (see Figure 1).

Unlike OC, which carries the opportunity to improve at any point in the building's lifetime, there is no room to improve EC once the materials are chosen and the building is constructed [14]. Material selection is, therefore, a crucial activity in building construction influencing EC reduction.

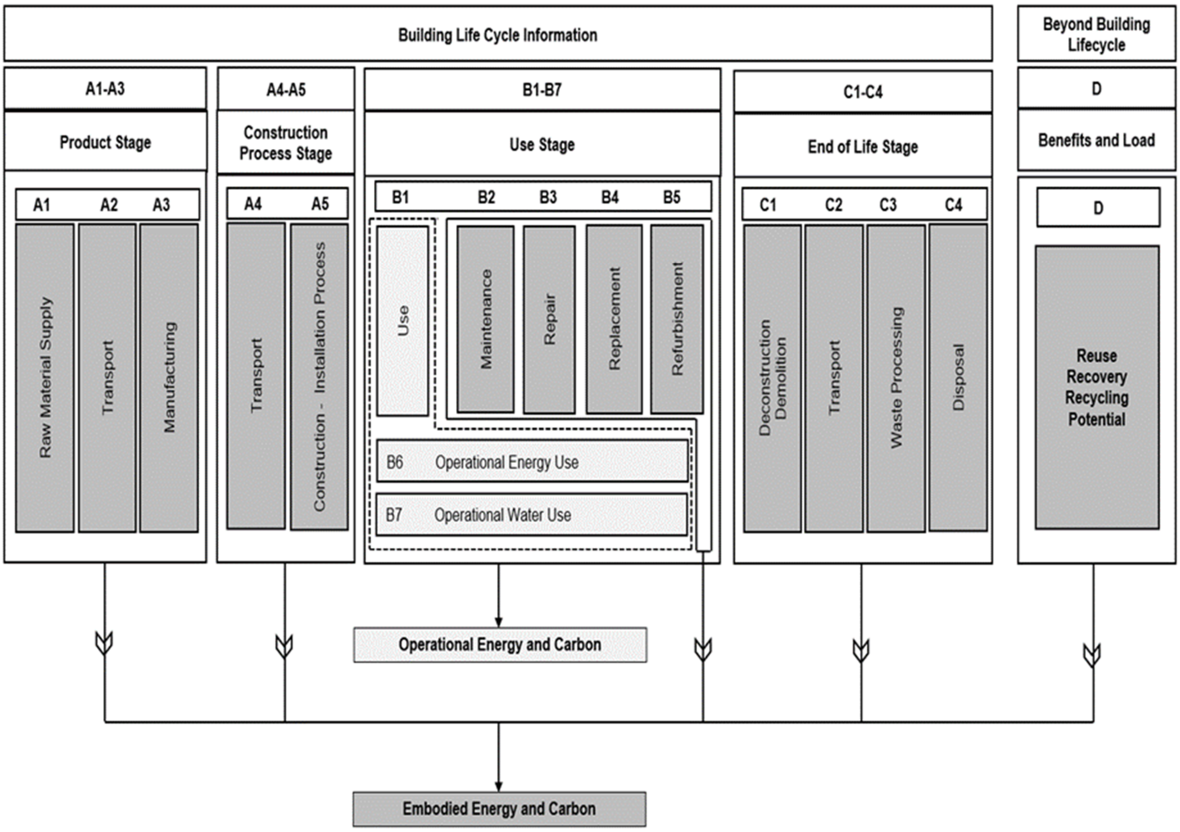

Figure 1. Operational carbon (OC) and embodied carbon (EC) emission stages (adapted from BS EN 15978:2011 Sustainability of construction works—assessment of environmental performance of buildings—calculation method [15]).

Ahmadian et al. [16] and Moussavi and Akbarnezhad [17] assert that EC needs to be considered as another criterion of material selection, which was traditionally based only on the criteria of cost, quality, durability, and assembly time. This means that building professionals involved in the material selection process can have a significant role in reducing EC by choosing suitable materials which save carbon without compromising other criteria.

In light of this, this study aims to explore the extent to which the building professionals consider EC as a criterion for material selection; in doing so, it also aims to identify any barriers that prevent building professionals from considering EC during material selection and drivers that motivate them to consider EC during material selection, and highlight the potential role of major industrial players to encourage the building professionals to use EC as a material selection criterion.

The Sri Lankan building and construction sector was chosen as the focus of this research. Sri Lanka is among the fastest developing countries in the Asian region [18]. Since the end of its civil war in the year 2009, its building sector has been rapidly developing, making a considerable impact on the environment by consuming large quantities of materials and energy [19]. This level of consumption is likely to be further increased with upcoming massive development projects in the country. Developing countries have been recognized as primary culprits with regard to the extraction and consumption of large quantities of materials due to their rapid buildings and infrastructure development projects [1,20], and the current increasing carbon trend in the global building sector has been triggered by their developments [1]. Therefore, a substantial part of the responsibility for reducing EC impacts of the global building sector lies with developing countries at present.

2. Literature Review

2.1. Importance of Material selection on EC Reduction

The overall EC of a building is directly proportional to its used materials and their quantities [21]. Therefore, material selection has a great opportunity to reduce the EC of buildings. WRAP [22], Nadoushani and Akbarnezhad [23], and Sandanayake et al. [24] indicate that for best results, material selection should take into account the EC impacts of alternative materials on the whole building life cycle, as some materials may contain high initial EC, but lower EC over the rest of the life cycle (and vice versa). Life cycle assessment (LCA) is the most refined and well-established methodology currently available for assessing environmental impacts associated with the life cycle of products, processes, and services [25]. This method has been widely used to assess the environmental impacts of various building materials and products over their life cycle. They provide quantitative data for a better comparison in the way of EC per functional unit of building materials or products [26]. Accordingly, suitable materials with lower EC impacts can be identified by analyzing the LCA information of alternative materials during material selection [22,27,28]. Table 1 summarizes EC reduction options associated with the selection of materials, followed by a brief description of each strategy. Although these options are attributed to different stages of a building as shown in Table 1, they should be taken collectively during material selection for a substantial reduction in EC.

Table 1. EC reduction options associated with the selection of materials (Source: WRAP [22] and UKGBC [29].

Building Stage	EC Reduction Options Associated with the Selection of Materials
Product	Select natural, reused or higher recycled content products or materials offering low carbon intensities
Construction Process	Select materials that are produced locally, thus reducing transport-related CO2 emissions
Repair and Maintenance	Select materials with high levels of durability and low maintenance through-life
End of Life	Select materials with higher reusability and recyclable content

Previous studies have revealed that the use of natural and bio-based materials has a high EC reduction potential, mainly due to their simple and low energy production methods [27,28,30]. Natural products, such as wood, natural wool, bamboo, water-based paints, and hemp and straw-based products, have relatively low EC contents compared to other traditional materials [22]. Additionally, as disclosed by Mah et al. [31], past research has indicated the possibility of reducing the carbon footprint of buildings by about 30% by selecting low carbon materials. The use of reclaimed products, such as bricks, roof tiles, timber, and timber products, also represent significant EC savings [22]. Further, WRAP [22] mentioned that using products with a higher recycled content tend to have lower EC than their equivalents with zero recycled content.

The selection of locally sourced materials is another strategy that could contribute significantly to EC reduction in buildings by reducing transport-related emissions [32,33]. However, WRAP [22] and Ahamadian et al. [16] mention that this strategy should be applied with caution, as the travel distance is not always sufficient to reduce EC, but transport mode, the quantity and the size of materials, and the number of trips needed must also be taken into account.

Another useful strategy is choosing durable and long-life materials with fewer maintenance requirements, which provide not only low EC impacts but also fewer impacts on operational energy and carbon [17,22].

Choosing materials and products with high reusability or recyclable content can also assist in reducing the need for landfill spaces and provide benefits beyond their life cycle [34,35]. Many studies have shown that concrete, steel, and aluminum have high reuse or recyclability potential, providing more opportunities to avoid the use of a large amounts of new materials in new construction.

2.2. Drivers for and Barriers to Considering EC Reduction during Material Selection

Although EC reduction strategies related to material selection have been discussed in the recent literature, few studies have been carried out on the drivers for and barriers to building professionals adopting these strategies. Giesekam et al. [36] revealed several drivers and barriers, but their investigation was limited to the strategy of adopting low carbon materials. Despite this, the drivers and barriers they identified were found to be applicable to all other material selection-related strategies.

According to Giesekam et al. [36], the key drivers that encourage to consideration of low carbon materials during material selection are moral convictions, client requirements, requirements of building assessment systems, other building professionals' requirements, and complying with organizational policies. Other drivers were also highlighted, but found to be less influential, including low cost, desirable aesthetics, reduced construction schedule, improving the health of the building, and regulatory requirements. In terms of barriers to the adoption of material-related EC measures, Giesekam et al. [37] carried out an extensive literature analysis, which revealed high cost of alternative materials, lack of material benchmark data and carbon information, a negative perception held by project professionals and the client or investor, low availability of alternative materials, negative experiences of colleagues, time-consuming nature to finalize the materials, industry culture, lack of existing regulatory frameworks, and lack of demonstration projects. Studies by WGBC [5] and Persson and Gronkvist [38] supported some of these findings. Giesekam et al. [37] organized these barriers into four main categories, namely, institutional, economic, technical and performance-related, and knowledge and perception. The drivers and barriers identified above are categorized and listed as in Table 2.

Table 2. Drivers for and barriers to considering EC reduction during the material selection (Source: Giesekam et al. [36] and Giesekam et al. [37].).

	Drivers	Barriers
Institutional	Complying with organization policies Regulatory requirements	Industry culture Lack of existing regulatory framework
Economic	Low cost Reduced construction schedule	The high cost of alternative materials Too time-consuming nature to finalize the materials
Technical and Performance-related	Requirements for building assessment systems Desirable aesthetics Improving the health of building	Lack of material benchmark data and carbon information lack of demonstration project Lack of alternative material options
Knowledge and Perception	Moral convictions Client requirements Other building professionals' requirements	The negative perception held by project professionals, the client or investor The negative experience of colleagues

3. Materials and Methods

This section gives an overview of the research methodology adapted in this study. As the first step, a comprehensive literature review was conducted, which identified the impact of the material selection process on EC reduction, EC reduction strategies associated with the material selection process, and drivers for and barriers to considering EC as a material selection criterion. The findings were used in the preparation of the questionnaire, which was employed as the data collection tool. The questionnaire comprised four main sections. The first section collected the demographic information of the respondents, such as their current job title, specialization, and years of experience in the building and construction sectors. The second section aimed to assess the respondents' influence level on building material selection. The third section measured their level of understanding of EC and reduction strategies associated with material selection. The fourth section comprised questions relating to the extent to which they considered EC as a material selection criterion (see Appendix A for the questionnaire).

Prior to the full-scale questionnaire survey, a pilot survey was conducted with three experts with more than ten years of industrial experience to pre-test the questionnaire for its appropriateness to achieve the aim of the study and validate it in terms of readability, feasibility, clarity of wording, layout, and style. Based on their comments, questions 2.1 and 3.1, which had used a 5-point Likert scale, were restructured for a 7-point Likert scale, and questions 4.2 and 4.3 were converted to multiple answer questions to reflect the respondents' true evaluations. The questionnaire was also fine-tuned for clarity of concepts and wording. The online survey was hosted using Google forms and made available from 27 July to 14 August 2020.

In a questionnaire survey, it is important that an appropriate research sample is generated to reflect the characteristics of the population(s) of interest [39]. A probability sampling technique was not feasible in this research due to the lack of availability of a complete list of the study population. Instead, a nonrandom sampling technique of convenience sampling was adopted. This enabled the recruitment of a set of representative individuals who were easily accessible, rather than selecting randomly from the entire population within the given period. The targeted respondents of the study included building professionals involved in the material selection process, such as architects, civil engineers, building services engineers, facilities managers, quantity surveyors, project managers, and sustainability managers. The questionnaire was distributed among 184 professionals who were identified through professional institutes' mailing lists and established contacts. The respondents were further invited to distribute the questionnaire among relevant professionals in their circle to increase the sample size of the survey. In total, 131 full responses were received, following two reminder emails. Figure 2 illustrates the composition of the respondents in terms of job title (see Appendix B1 for further information about respondents). The highest number of responses was received from engineering professionals, such as civil and building services engineers, representing 40% of total responses, whilst the lowest number of responses was received from sustainability managers, representing 8%. Responses from architects, facilities/maintenance managers, and quantity surveyors represented 16%, 15%, and 12% of total responses, respectively; the final 9% were project managers.

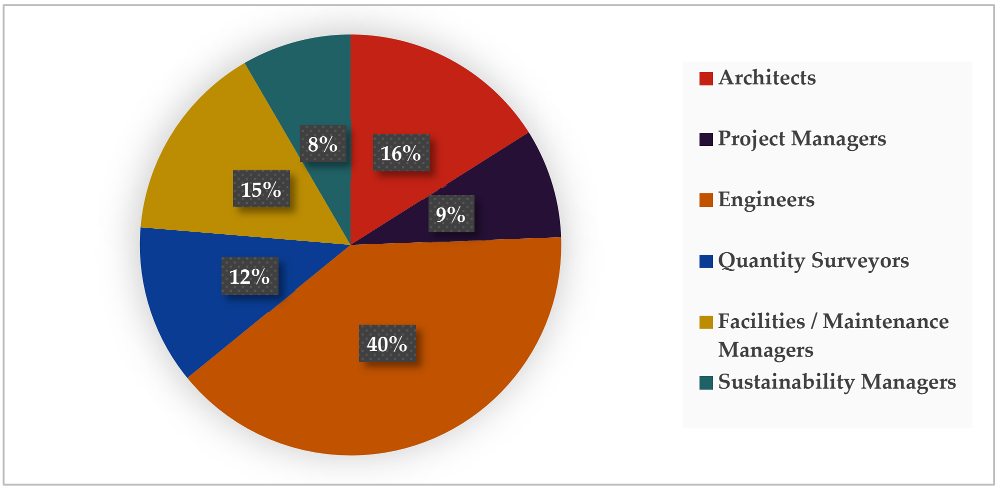

Figure 2. Composition of the respondents.

Respondents were asked to indicate their amount of experience in the building industry. Figure 3 summarizes their responses, and Appendix B2 provides the basic statistics of this result. The highest number of respondents had 0–5 years of experience, representing 34% of total respondents. Futhermore, 30% of respondents had 5–10 years of experience, 24% had more than 15 years of experience, and 12% had 10–15 years of experience.

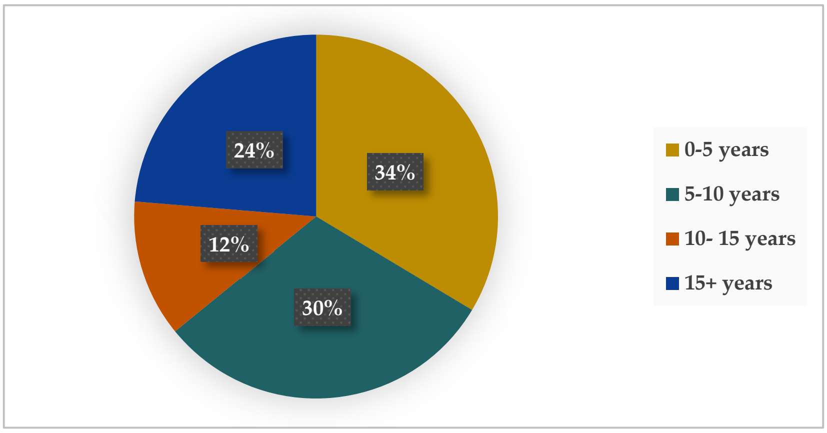

Figure 3. Experience of the respondents.

The collected data were then processed and analyzed using descriptive and inferential statistics. The techniques included frequency distributions, Spearman's rank correlation, or Spearman's rho (r_s), and Relative Important Index (RII). The frequency distribution method was used to analyze the number of occurrences of each response selected by the survey participants in each question, using tables, pie charts, and bar charts. Spearman's rho (see Equation (1)) was used to measure the correlation among variables of influence on material selection, knowledge of EC, and consideration of EC as a material selection criterion (see Section 4.4 for details). This test was applied over the Pearson's correlation test as these variables were ordinal. Generally, the correlation coefficient value falls between +1 and -1. While a positive correlation coefficient indicates a positive relationship between variables, a negative correlation coefficient expresses a negative relationship. A correlation coefficient of zero indicates no relationship between variables.

$$r_s = 1 - \frac{6 \sum d_i^2}{n\,(n^2 - 1)} \quad (1)$$

where

d_i is the difference between the two ranks of each observation;

n is the number of observations.

RII analysis allowed us to prioritize different players in the building and construction sector according to their importance in the involvement of promoting EC as a material selection criterion (see Section 4.6 for details). Equation (2) was used to calculate RII.

$$Relative\ Important\ Index\ (RII) = \frac{\sum W}{A \times N}\ (0\ \leq RII\ \geq 1) \quad (2)$$

where

W is the weighting as assigned by each respondent on a scale of 1–7 with one implying no importance at all and 7 extreme importance;

A is the highest level on the Likert Scale (7 is the highest level on the given Likert Scale);

N is the total number of respondents.

Further, five important levels were transformed from RI values: high (0.80 ≤ RI ≤ 1.00), high-medium (0.6 ≤ RI ≤ 0.79), medium (0.4 ≤ RI ≤ 0.59), medium-low (0.2 ≤ RI ≤ 0.39) and low (0 ≤ RI ≤ 0.19).

4. Results

4.1. Influence of Respective Professionals on Material Selection

The respondents were initially asked to rate their own influence level on material selection on a 7-point Likert scale where 7 represents “primary influence” and 1 represents “no influence”. This enabled the researchers to ascertain respondents’ current contributions to decision making on material selection, prior to assessing their knowledge and consideration of EC as a material selection criterion. As illustrated in Figure 4, two-thirds of respondents (69%) indicated that they had at least a moderate level of influence. Facility managers stand out as the respondents with the most primary influence over material selection, followed by project managers, while architects were the most influential when considering both “primary” and “very high” influence levels together. Furthermore, 11% of respondents showed no influence at all, and this proportion largely comprised quantity surveyors. See Appendix B3 for the basic statistics of this result.

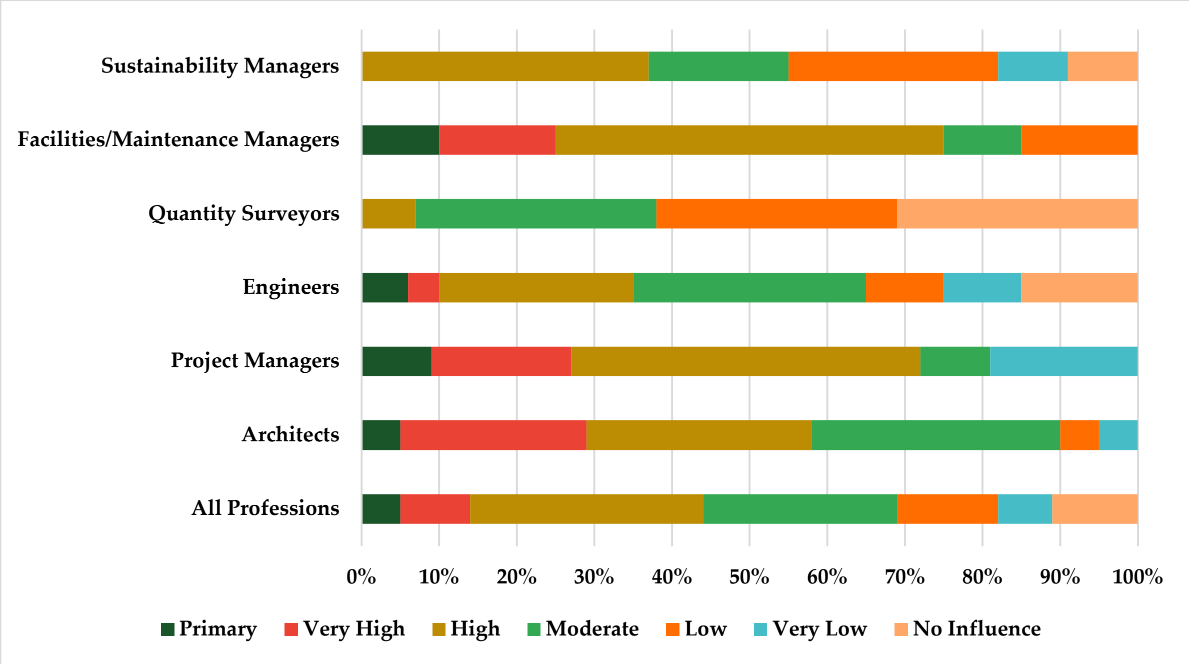

Figure 4. Influence levels of respondents on material selection.

4.2. Knowledge of EC and Reduction Strategies Associated with Material Selection

Figure 5 summarizes the respondents' answers about their level of understanding of the importance of EC reduction and reduction strategies associated with material selection. To assess their understanding level, a 7-point Likert scale was used in which 7 represents "excellent" and 1 represents "know nothing". As illustrated in Figure 5, about 62% of the respondents indicated that they had at least a fair level of knowledge, while the remaining 38% indicated a low or zero knowledge level, largely representing project managers, engineers, and quantity surveyors. The basic statistics of this result can be found in Appendix B4.

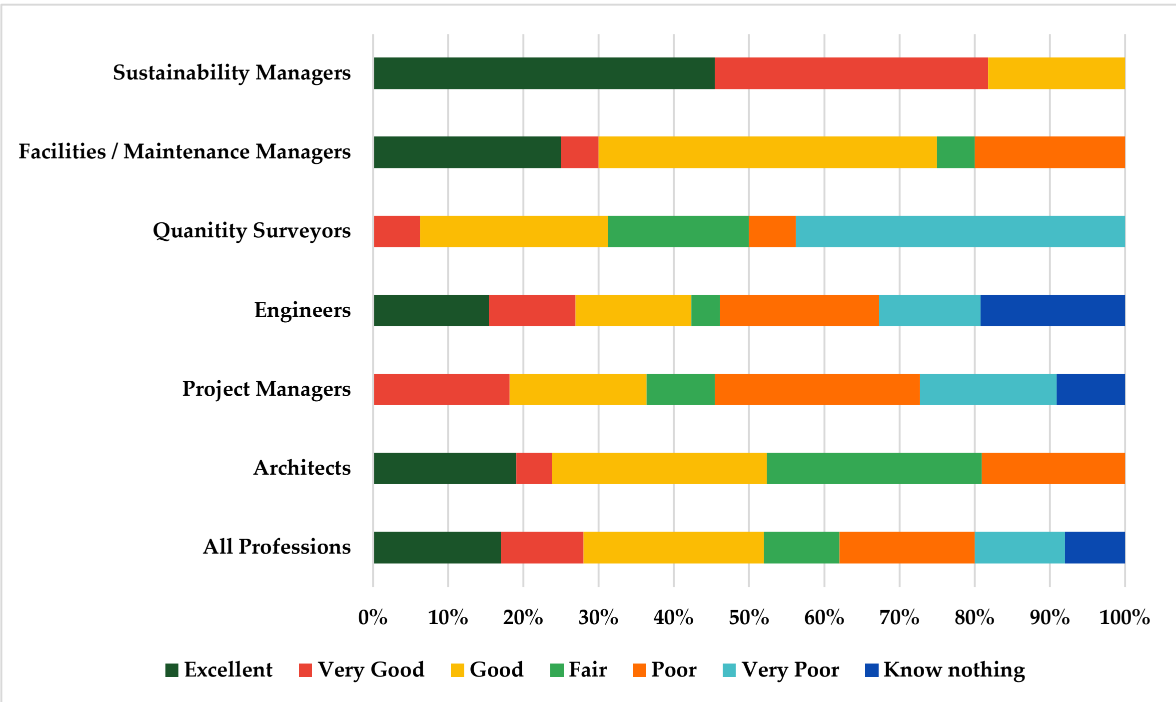

Figure 5. Level of knowledge on EC and reduction strategies associated with material selection.

4.3. Consideration of EC as a Material Selection Criterion

As illustrated in Figure 6, more than half of the respondents (54%) did not consider EC as a criterion for material selection. Of the remaining 46% of respondents, 14% had considered EC during material selection for just one project, and 32% had considered it for more than one project. None of the survey participants had considered EC during the material selection process for all the projects that they had been involved with. Please find the basic statistics of Figure 6 in Appendix B5.

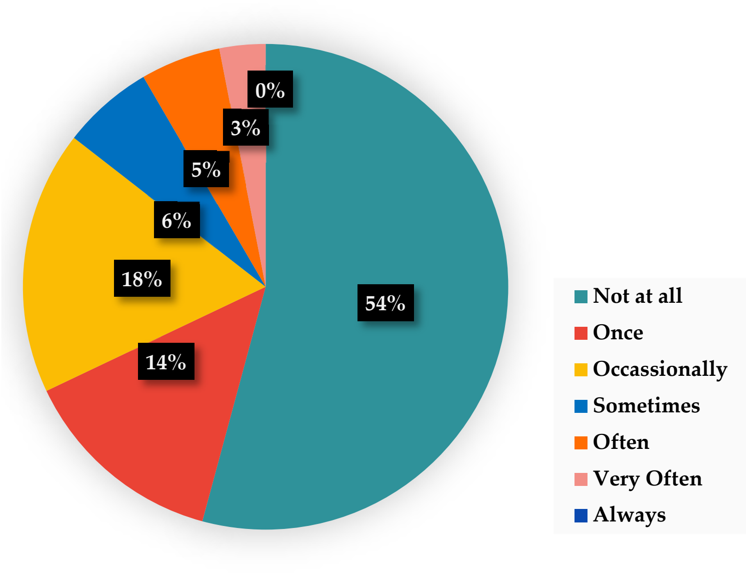

Figure 6. The extent to which the building professionals consider EC as a material selection criterion.

These results were broken down by respondents' professions, as in Table 3. Facilities/maintenance management professionals were most likely to have considered EC as a material selection criterion, while quantity surveying professionals were least likely.

Table 3. No. of respondents who have considered EC as a material selection criterion.

Building Profession	Total Respondents	No. of Respondents Who Have Considered EC as a Material Selection Criterion	% of Respondents Who Have Considered EC as a Material Selection Criterion
Architecture	21	9	43%
Engineering	52	25	48%
Project Management	11	6	55%
Quantity Surveying	16	2	13%
Facilities/Maintenance Management	20	13	65%
Sustainability Management	11	5	45%
All Professions	131	60	46%

Respondents that had considered EC as a material selection criterion for at least one project were asked to disclose the reduction strategies that they had considered in their projects, with the four reduction strategies identified in Section 2.1 being offered as choices. The summary of the findings is presented in Table 4. Slightly more than half of these respondents had considered the strategies of selecting materials with high durability and low maintenance (32/60), or of sourcing locally manufactured products (31/60) for their projects. About 45% (27/60) of respondents had considered choosing reusable or recyclable/recycled materials, while 25% (15/60) of respondents had considered the strategy of using low carbon materials during material selection for their projects.

Table 4. EC reduction strategies used by respondents.

EC Strategies	No. of Respondents	Percent of Cases
Select low carbon materials	15	25%
Local sourcing	31	51%
Select materials with high durability and low maintenance	32	53%
Select reusable or recyclable/recycled materials	27	45%

4.4. Relationship between Influence on Material Selection, Knowledge of EC and Consideration of EC as a Material selection Criterion

Having identified that less than half of respondents had considered EC as a material selection criterion, the researchers then attempted to explore whether there was a relationship among considering EC as a material selection criterion, respondents' levels of influence over material selection, and knowledge of EC reduction strategies associated with material selection. The results of Sections 4.1, 4.2, and 4.3 were subjected to a nonparametric test of Spearman's correlation coefficient (r_s). The results are presented in Table 5. The test revealed that the r_s between the EC consideration as a material selection criterion and knowledge of EC reduction strategies associated with material selection is 0.467, which indicates a weak, positive correlation. This means that respondents who are more likely to consider EC as a material selection criterion do not necessarily have knowledge of EC reduction strategies. The correlation between EC consideration as a material selection criterion and influence on material selection equals 0.314, which is a weak, positive correlation, suggesting that EC consideration as a material selection criterion is not strongly associated with having an influence on material selection. This suggests that there could be other factors that affect the consideration of EC as a material selection criterion. The section below identifies the barriers and drivers that have affected the consideration of EC as a material selection criterion in the Sri Lankan buildings and construction sector.

Table 5. Correlation among consideration of EC as a material selection criterion, knowledge of EC and reduction, and influence on material selection.

	Knowledge of EC and Reduction Strategies	Influence on Material Selection	Consideration of EC as a Material Selection Criterion
Consideration of EC as a material selection criterion	0.467	0.314	1.000

4.5. Barriers to and Drivers for Considering EC as a Material Selection Criterion

Respondents were questioned about the drivers that encouraged them to consider EC as a selection criterion when making material selection decisions, as well as the barriers that prevented them from doing so. The drivers and barriers identified through the literature review in Section 2.2 were brought to the respondents' attention, with only barriers being presented to those respondents who had not previously considered EC during material selection, while drivers were presented to respondents who had considered EC during material selection for at least one project. The results are illustrated in Tables 6 and 7.

Table 6. Barriers to considering EC during the selection of the materials.

Barriers	Responses	Percent of Cases
Lack of knowledge and skills	38	53%
Lack of material benchmark data and carbon information	44	62%
The negative perception held by other project professionals	22	31%
The negative perception held by the client or investor	20	28%
Low availability of alternative materials	64	90%
The negative experience of colleagues	12	16%
Time-consuming nature to finalize the materials	35	49%
The high cost of low carbon and efficient materials/products	46	65%
Industry culture	35	49%
Not yet mandated by the existing regulatory framework	67	94%
Lack of demonstration projects	19	27%

Table 7. Drivers for considering EC reduction during the selection of materials.

Drivers	Responses	Percent of Cases
Felt morally obliged	17	28%
Realized its benefits from previous experience	37	62%
Earned points towards building assessment systems	39	65%
Client required it	23	38%
Other project professionals required it	9	15%
Fitted with organization policy	9	15%
Regulatory requirements	0	0%

Table 6, focusing on barriers, shows that the majority of respondents (>90%) indicated that the lack of regulations imposed by governing bodies, and the lack of low carbon materials had prevented them from considering EC during material selection. Half or more of respondents (49% > 65%) cited the following barriers to considering EC: high cost of low carbon materials, lack of material benchmark data and carbon information, lack of technical knowledge and skills, finding it too time-consuming to finalize the materials, and industry culture. Less than one third of respondents (<31%) cited the following barriers: lack of project demonstrations, a negative perception held by the client or investor, a negative perception held by other project professionals, and colleagues' negative experiences.

Table 7, on drivers for EC consideration, indicates that almost two thirds of respondents (62%–65%) had been motivated to consider EC during material selection by building assessment systems or the benefits realized from previous experience. The requirements of clients, moral conviction, other professionals' requirements, and requirements of organizational policies were each recognized as drivers by less than half of respondents. Importantly, none of the respondents identified regulatory requirements as a driver for this subject matter, which is unsurprising, as no policies and regulations have been implemented on EC reduction in Sri Lanka as yet [40].

4.6. Involvement of Different Players in the Industry to Promote EC as a Material Selection Criterion

Respondents were asked to rate different players involved in the building and construction sectors according to how important they perceived them to be in promoting EC as a material selection criterion. The players included building professional bodies, the government, environment-related organizations, activist groups, and the general public. The RII technique was employed to rank their importance from the highest to least importance. The summary of the RII analysis can be shown as in Table 8.

Table 8. Ranking stakeholders based on their intervention in promoting EC as a material selection criterion.

Different Players	RII	Rank Based on the Level of Importance to Intervention	Importance Level
Building Professional Bodies	0.85	2	high
The Government	0.89	1	high
Environment-Related Organizations	0.84	3	high
Activists Groups	0.73	4	high–medium
General Public	0.73	4	high–medium

RII analysis indicated that that the intervention of all players is crucial to promote EC as a material selection criterion. The government scored the highest RII of 0.89, followed by professional bodies (0.85) and environment-related organizations (0.84). These three players were highlighted to have a high importance level, while activist groups and the general public were perceived to have a high–medium importance level, with an RII of 0.73.

5. Discussion

This study aimed to explore the extent to which the building professionals in Sri Lanka consider EC as a material selection criterion. As EC is associated with the materials and construction processes used throughout a building life cycle, it is vital to consider EC minimization strategies associated with materials during material selection. Once the materials have been selected and embedded in the construction, the opportunity to reduce the EC impacts of buildings is much lower. This means that building professionals involved in material selection decisions have a pivotal role in minimizing the EC of buildings.

Like many other countries, Sri Lanka has focused primarily on OC to date. However, with the increasing importance of the EC share of whole building life cycle carbon, the attention of researchers and practitioners involved in the building and construction sectors of Sri Lanka has been gradually shifting towards EC. Few previous studies in the existing literature have been conducted on EC estimation and reduction in the Sri Lankan context, and the importance of EC reduction is yet to be fully realized [40–42]. It is anticipated that the findings of this research will contribute to the existing body of knowledge and help to raise awareness among relevant policymakers, researchers, and practitioners of the importance of EC reduction.

The findings of the survey indicated that the architecture professionals have the highest influencing powers on the selection of the material compared to other professionals in the construction industry. This is supported by Giesekam et al. [36] and Arup and WBCSD [43], who stated that the architecture profession remains the main influencer followed by engineers in material selection for construction projects. However, this can be varied depending on the project, the country or region, and the stakeholders involved in the project. For example, in Sweden, material-related decisions are mainly maden by clients and contractors [44]. It is surprising that the quantity surveyors were found to have the lowest influencing powers on material selection. Quantity surveyors, as the cost estimators whose role is to enhance the value for money of a construction project, might be expected to have substantial authority and involvement in material selection decisions.

Regarding knowledge of EC and reduction strategies, the survey results indicated that about half of the respondents have fair or low knowledge. This finding is supported by Abeydeera et al. [45] who found that Sri Lankan construction professionals had poor awareness of carbon emissions, especially EC emissions and related mitigation strategies. As mentioned before, this is likely to be mainly due to the slow uptake of EC aspects within the Sri Lankan building and construction industries.

More than half of respondents (54%) cited that they had not considered any EC reduction strategies related to material selection. An analysis was carried out to examine the correlation between building professionals' influence on material selection, their knowledge of EC, and their consideration of EC during material selection to determine whether there is a connection among these factors that prevents EC consideration during material selection. The analysis revealed that respondents' influence on material selection and knowledge of EC have no strong impact on the consideration of EC in material selection. The results indicated a weak positive relationship between knowledge of EC and consideration of EC as a building material selection criterion, whereas the relationship between influence levels on material selection and consideration of EC as a building material selection criterion is a weak positive one too. It is evident that building professionals' knowledge of EC and influence levels on material selection do not directly impact the consideration of EC as a material selection criterion in Sri Lanka. Respondents who said they did not consider EC during material selection were further questioned about the reasons why they did not do so, with the majority of respondents citing the absence of regulations imposed by regulatory bodies obliging them to do so, and the lack of low carbon materials. Contrary to these findings, in a study conducted in a UK context, Watson et al. [46] found that the high cost of alternative materials, lack of technical knowledge, and lack of client understanding were the major barriers in the UK. These findings emphasize that the barriers can be different depending on the country, type of project, and the type of building professionals involved.

Respondents who had previously considered EC during material selection revealed that they had been mainly motivated to do so by building assessment tools and their previous experience. Currently, many different building assessment systems are used in the Sri Lankan building industry. Green Building Rating System Sri Lanka, Leadership in Energy and Environmental Design (LEED), and Building Research Establishment Environmental Assessment Method (BREEAM) are examples of leading green building rating systems that are used in the current Sri Lankan building sector. In all of these rating systems, materials and resources are key aspects which offer considerable credit values for choosing low carbon materials, local sourcing, and reusing and recycling of materials. Therefore, it is not surprising that building professionals have been motivated by building rating systems.

As a potential solution to the low incidence of consideration of EC during material selection, the survey respondents suggested that the involvement of various building actors, such as the government, professional bodies, environmental organizations, activist groups, and the public, is important to promote EC consideration during material selection. If the government were to intervene by introducing mandatory regulations or policies, this would have a major influence on ensuring EC was considered for all projects, as it would then be a legal requirement. This is considered to be the most sustainable way of encouraging building professionals to consider EC during material selection, and in doing so reduce the EC share of buildings.

As the next step in this research, a greater understanding of material ratings in terms of lower EC impacts needs to be developed, in order that building professionals have access to information to help them make decisions on the right materials or products to select in order to minimize EC. A concept such as material passports, developed to select materials to contribute to a more circular economy, could be adapted to reflect the EC impacts of materials using a written document or a tool. Such an approach would help not only to reduce EC impacts of buildings but also to drive developing countries, such as Sri Lanka, towards a circular economy. Finally, the roles towards maximizing material selection decisions for EC reduction can be outlined as in Figure 7.

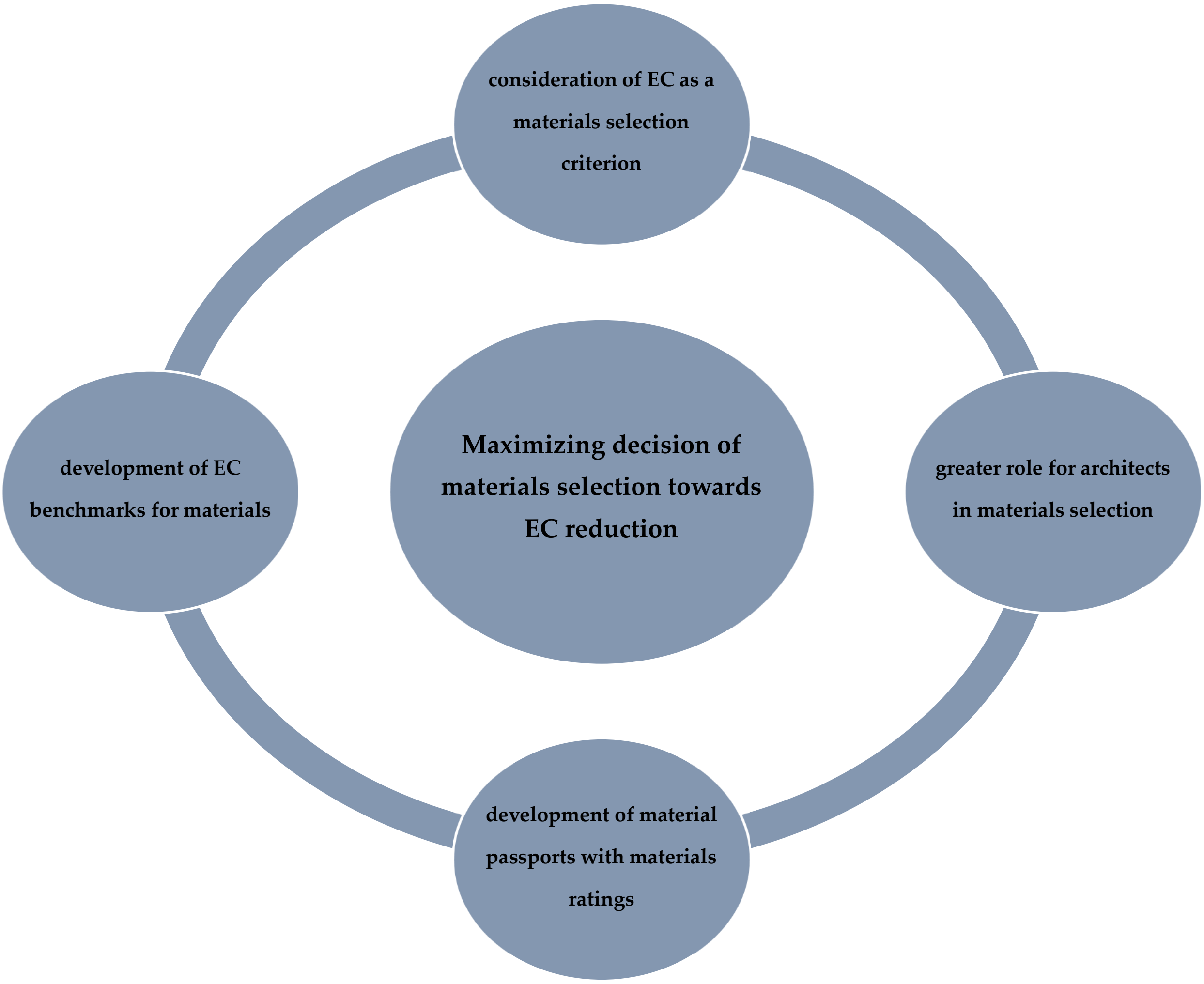

Figure 7. Roles towards maximizing material selection decision for EC reduction.

6. Conclusions

EC emissions are mainly associated with the materials and construction processes used throughout a building life cycle. In order to reduce EC, it is, therefore, necessary to explore the decisions made by building professionals at the material selection stage. This study was conducted in the context of the Sri Lankan building and construction sectors. The experiences and perceptions of building professionals in Sri Lanka were assessed through a questionnaire survey and analyzed to identify their level of consideration of EC reduction during material selection. The targeted respondents included architects, civil engineers, building services engineers, facilities managers, maintenance managers, quantity surveyors, project managers, and sustainability managers.

The survey results indicated that about half of the respondents (54%) had not considered EC during material selection, suggesting that overall, EC consideration during material selection in Sri Lanka is low. The lack of regulatory frameworks and lack of availability of low carbon materials were identified as the most common reasons preventing respondents from considering EC during material selection. The current legal and regulatory framework, government policies, and procedures in Sri Lanka do not play a strict role in reducing EC emissions of buildings. The adoption of new regulatory frameworks is, therefore, considered essential to promote the application of EC reduction strategies during the material selection process in Sri Lanka. Respondents who had considered EC during material selection had been mainly motivated by building rating systems and their previous experience. Therefore, survey respondents suggested that, along with the Sri Lankan government, professional bodies, environmental organizations, activist groups, and the general public may have a significant role to play in terms of encouraging the building sector to consider EC during material selection and thereby helping to reduce the EC share of buildings. The next step in this research includes developing a material rating system in the Sri Lankan context, which provides information on the EC impacts of materials and assists building professionals in making decisions on the right materials or products to minimize EC.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A. Questionnaire

Section 1- General Information of Respondents

1.1 What is your job title (ex: Project Manager, Civil Engineer, Facilities Manager)?

…………………………………………………..

1.2 What is your area of specialisation (ex: Architecture, Engineering, Environmental Sustainability)?

…………………………………………………….

1.3 How many years of experience do you have in the building sector?

0–5 years	5–10 years	10–15 years	15+ years

Section 2- Influence on Selecting Building Materials

2.1 How much influence do you have in your organisation when selecting building materials?

No Influence
Very low
Low
Moderate
High
Very high
Primary

Section 3- Knowledge of Embodied Carbon and Reduction Strategies

3.1 What is your level of understanding on embodied carbon emissions and importance of embodied carbon reduction?

Know nothing
Very poor
Poor

Fair
Good
Very good
Excellent

Section 4- Embodied Carbon Emission as a Decision-Making Criterion

4.1 Have you considered embodied carbon as a decision-making criterion when selecting building materials?

Not at all
Once
Occasionally
Sometimes
Often
Very often
Always

4.2 If you have considered EC for at least for one project, what are strategies you have considered? Select all the relevant options

Select low carbon materials
local sourcing
select high durable and low maintenance materials
select reusable or recyclable/recycled materials
Other …………………………………………………………

4.3 If you have considered EC at least for one project, what persuaded you? Please select all relevant answers.

Felt morally obliged
I have previously realised its benefits and that motivated me
Requirements of building assessment system/s to earn points
Client required it
Other project professionals required it
Compiled to the organisation policy
Regulatory requirements
Other …………………………………………………………………

4.4 If you have not considered EC for any project, what would be the reasons? Please select all relevant answers.

Lack of technical knowledge and skills to compare alternative building materials in terms of embodied carbon emissions
Lack of material benchmark data and carbon information
Negative perception held by other project professionals
Negative perception held by the client or investor
Low availability of alternative materials
Negative experience of colleagues
Too time consuming to finalise the materials
High cost of low carbon and efficient materials/products
Industry culture
It is not yet mandated by the existing regulatory framework
Lack of demonstration projects
Other ………………………………………………………

4.5 As you believe, how important the intervention of below figures to promote embodied carbon emission as a decision-making criterion for material selection?

	Not at all Important	Slightly Important	Moderately Important	Neutral	Important	Very Important	Extremely Important
Professional bodies							
The government							
Environmental organizations							
Activist groups							
General public							

Appendix B. Basic Statistics

Appendix B1. Composition of Respondents

Profession of Respondents	Number of Respondents	Percentage (%)
Architects	21	16.03%
Project Managers	11	8.40%
Engineers	52	39.69%
Quantity Surveyors	16	12.21%
Facilities/Maintenance Managers	20	15.27%
Sustainability Managers	11	8.40%
Total	131	100.00%

Appendix B2. Experience of Respondents

Experience in the Industry	Number of Respondents	Percentage (%)
0–5 years	44	34%
5–10 years	40	31%
10- 15 years	16	12%
15+ years	31	24%
Total	131	100%

Appendix B3. Influence Levels of Respondents on Material Selection

	Primary	Very High	High	Moderate	Low	Very Low	No Influence
All Professions	5%	9%	30%	25%	13%	7%	11%
Architects	5%	24%	29%	32%	5%	5%	0%
Project Managers	9%	18%	45%	9%	0%	19%	0%
Engineers	6%	4%	25%	30%	10%	10%	15%
Quantity Surveyors	0%	0%	7%	31%	31%	0%	31%
Facilities/Maintenance Managers	10%	15%	50%	10%	15%	0%	0%
Sustainability Managers	0%	0%	37%	18%	27%	9%	9%

Appendix B4. Level of Knowledge on EC and Reduction Strategies Associated with Material Selection

	Excellent	Very Good	Good	Fair	Poor	Very Poor	Know nothing
All Professions	17%	11%	24%	10%	18%	12%	8%
Architects	19%	5%	29%	29%	19%	0%	0%
Project Managers	0%	18%	18%	9%	27%	18%	9%
Engineers	15%	12%	15%	4%	21%	13%	19%
Quantity Surveyors	0%	6%	25%	19%	6%	44%	0%
Facilities/Maintenance Managers	25%	5%	45%	5%	20%	0%	0%
Sustainability Managers	45%	36%	18%	0%	0%	0%	0%

Appendix B5. The Extent to Which the Building Professionals Consider EC as a Material Selection Criterion

Extent of Consideration	Number of Respondents	Percentage (%)
Not at all	71	54%
Once	18	14%
Occasionally	23	18%
Sometimes	8	6%
Often	7	5%
Very Often	4	3%
Always	0	0%
Total	131	100%

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